Physics 226: Particle Physics Phenomenology
Lecture 1: Introduction

Fall 2016
August 25 , 2015

- Primary theme of this class:
  - Interplay between theory and experiment
    - Suprising experimental results lead to theoretical breakthroughs
    - Brilliant theoretical ideas both guide experiment and allow us to interpret measurements

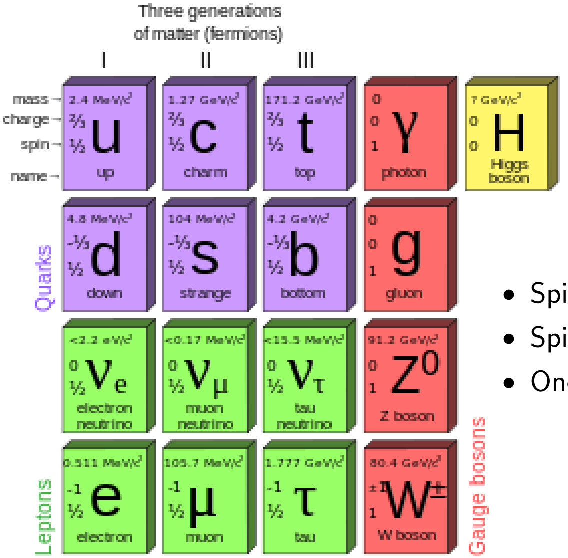
- Understanding of particle physics expressed in the Lagrangian of the "Standard Model":
  - A misleading name!
    - SM is a real theory with well-developed phenomenology
    - Testable predictions
    - Describes all experimental results (except perhaps neutrino mass)

Term "Standard Model" is an indication of our greed

- Reminds us that there are many unanswered questions
  - Does particle physics provide a solution for Dark Matter?
  - Why is gravity so much weaker than the other forces?
  - Why is there so little anti-matter in the Universe?
  - Are there extra space-time dimensions?
  - Why are there 3 generations of quarks and leptons?

- Answers to any of these questions would revolutionize our view of the world!
  - Mainstream particle physics experiments today are searching for phenomena that address all these issues

The Standard Model Particles



- Spin $\frac{1}{2}$ matter fields
- Spin 1 force carriers
- One fundamental scalar

Particle physics framework based on development of quantum gauge theories

- You will study quantum gauge theories in detail in Physics 232
- Simplest such theory: Quantum Electrodynamics (QED)
  - Developed in the 1950's
  - Tested to 7 significant digit precision
  - Exhibits a number of remarkable properties that are typical of all gauge theories
    - Need for renormalization: process of subtracting unobservable infinities and retaining small, finite observable corrections
    - Identification of spin 1 field as force carrier
    - Strength of interaction depends on a universal coupling constant (α)

Introduction to QED (I)

- Describes behaviour of spin $\frac{1}{2}$ fermions and a 4-vector potential (E&M)
- As in classical E&M, $\mathcal{L}$ has a manifest global symmetry
  - Freedom to redefine vector potential by a gauge tranformation, which does not change the equations of motion
- New in QED:
  - Postulate $\mathcal{L}$ is invariant under *local* gauge tranformations
    - This forces addition of an interaction term
    - Fermions interact with field; strength of interaction proportional to particle's charge
  - Local gauge invariance determines the nature of the fermion-field interaction, forces the photon to be massless and insures conservation of electric charge

Introduction to QED (II)

Classically:

$$\begin{aligned} A^\mu &= (V, \vec{A}) \\ A^\mu &\to A^\mu - \partial^\mu \Lambda(x) \end{aligned}$$

Quantum Theory:

$$\psi(x) \to e^{i\theta}\psi(x)$$

Dirac Eq:

$$\mathcal{L}_{free} = \overline{\psi}\,(i\gamma^\mu \partial_\mu - m)\,\psi$$

Postulate local rather than global gauge invariance:

$$\psi(x) \to e^{i\theta(x)}\psi(x)$$

Eq. of motion not invariant unless we make the following changes

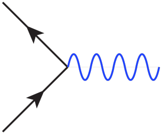
$$\begin{aligned} \partial_\mu &\to \mathcal{D}_\mu \equiv \partial_\mu + iqA_\mu(x) \\ A_\mu(x) &\to A_\mu(x) - \partial_\mu \theta(x) \\ \psi(x) &\to e^{i\theta(x)}\psi(x) \end{aligned}$$

The QED Lagrangian

$$
\begin{aligned}
\mathcal{L}_{QED} &= \overline{\psi}\left(i\gamma^{\mu}\mathcal{D}_{\mu} - m\right)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\
&= \overline{\psi}\left(i\gamma^{\mu}\partial_{\mu} - q\gamma^{\mu}A_{\mu} - m\right)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\
&= \mathcal{L}_{Dirac} - J^{\mu}A_{\mu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}
\end{aligned}
$$

where $J^{\mu} = \ q\gamma^{\mu}$

- Local gauge invariance defines interaction term
  - Interaction of charged current J^{μ} with photon
  - Photon must be massless: mass term $\frac{1}{2}M_A^2 A^{\mu}A_{\mu}$ would destroy gauge invariance



QED is a simple field theory for many reasons

- Dirac Eq plus knowledge of classical E&M makes choice of Lagrangian "obvious"
- QED vector potential is pretty simple:

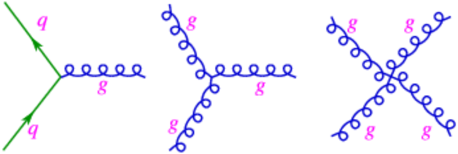
$$[A_\mu, A_\nu] = 0$$

  no photon self-interactions (photon has no charge)
- There is only 1 kind of photon
- There are no hidden symmetries or other wrinkles

How is the SM Different?

Strong Interactions (I)

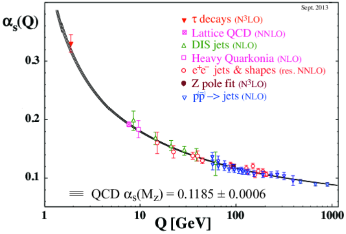
- Looks like QED, except gauge field more complicated
- Instead of scalar electric charges, fermion fields (ψ) have color charge describes as a triplet of SU(3)$_{color}$
- Gluons are a color octet of SU(3) (8 gluon states)
  - $[A_i, A_j] \neq 0$ for $i \neq j$ " non-abelian"
  - Equivalent of $F_{\mu\nu}$ contains an additional term that depends on this commutator
  - Gluons interact with each other as well as with quarks



- Strong coupling constant α_s plays same role in theory as α does in QED

Strong Interactions (II)

- In all gauge theories, coupling strength depends on momentum transfer in interaction (Q)
- Essentially a polarization effect
  - Virtual particle-antiparticle pairs produced in vacuum
  - These shield "bare charge" of interacting particle
    - In QED, coupling increases with energy
    - In QCD, due to gluon self-coupling, coupling varies more rapidly and decreases withe energy

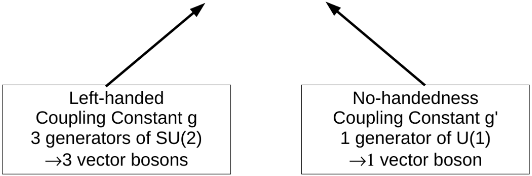


Behaviour of α_s

- Low Q: non-perturbative
- High Q: perturbation theory OK
  - $\alpha_s \gg \alpha$: slower PT convergence

Weak Interactions (I)

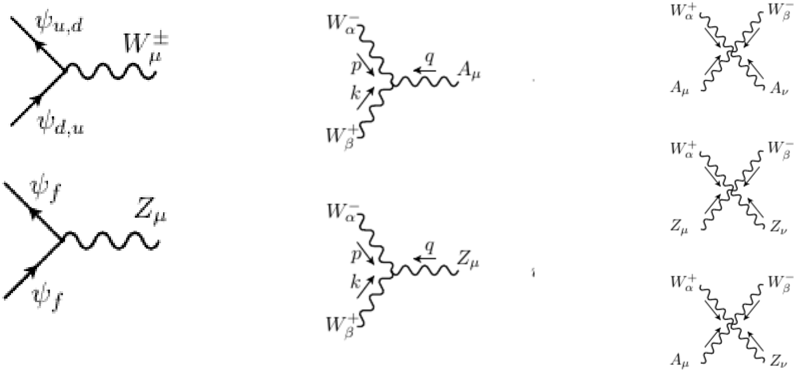
- Like Strong Interactions, gauge group is non-abelian
  - But wrinkles different from the Strong Interaction case
- Attempt to unify electromagnetic and weak interactions, but in fact there are two coupling constants
  - Gauge group is SU$(2)_L\times$ U(1)



  - However, g and g' are not EM and weak couplings
    - Mixing among components
    - EM basis is a combination of neutral components of SU$(2)_L$ and U(1)

Weak Interactions: The Force Carriers

- Three vector bosons': W^+, W^-, Z^0
- $W^\pm$ responsible for β-decay: changes quark and lepton flavor
- Z also couples to quarks and leptons (similar to photon)
- Triple and Quartic couplings of gauge bosons to each other



Weak Interactions: The bosons have mass

- Weak interactions not mediated by a massless field
  - Short range force
- "Weakness" comes from mass of force mediator

$$G_F \sim 10^{-5}\ \mathrm{GeV}^{-2} \Rightarrow g_W/M_W^2$$

- But how to incorporate massive boson into gauge theory?
  - Gauge invariance does not allow addition of a mass term directly into the LaGrangian
  - The solution: Electroweak Symmetry Breaking and the Higgs mechanism
    - Introduce a scalar field and a symmetry
    - Change physical basis
  - M_W and M_Z predicted in terms of e and 1 additional parameter $(\sin^2\theta_W)$

The Standard Model Lagrangian

$$
\begin{aligned}
\mathcal{L} \;=\; & -\frac{1}{4} F^{a}_{\mu\nu} F^{a\mu\nu} + i\bar{\psi} D\psi && \Leftarrow \text{gauge sector} \\
& + \psi_i \lambda_{ij} \psi_j h + \text{h.c.} && \Leftarrow \text{flavour sector} \\
& + |D_\mu h|^2 - V(h) && \Leftarrow \text{Higgs sector} \\
& + \frac{1}{M} L_i \lambda^{\nu}_{ij} L_j h^2 \text{ or } L_i \lambda^{\nu}_{ij} N_j && \Leftarrow \nu \text{ mass sector}
\end{aligned}
$$

- $\mathcal{L} = \mathcal{L}_{QCD} + \mathcal{L}_{EW}$
- Gauge group: $\mathrm{SU}(3) \times \mathrm{SU}(2)_L \times \mathrm{U}(1)$

Beyond the SM

- In SM, all forces described by local gauge theories
  - What about gravity?
    - Spin-2 gravaton not easily added
  - String theory a natural extension
    - Gauge theory as a low energy manifestation
- All forces defined in terms of symmetry properties
  - Can embed gauge group in larger group that "unifies" them
    - One coupling constant rather than 3
    - Grand Unified Theory (GUT)
  - Expected scale for unification $\sim 10^{15}$ GeV
    - Extra space-time dimensions can bring scale down
  - Can also add additional symmetries
    - Eg Supersymmetry (SUSY)

The Role of Experiment

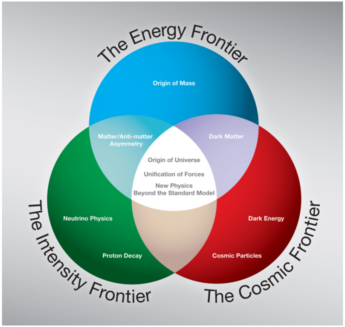
- In QED:
  - Observation: EM has global gauge invariance
  - Theory: Postulate of local invariance leds to predictions
  - Experimental measurements validated approach
    - $g - 2$, Lamb shift
- In SM:
  - Matter content determined from experiment
  - Underlying symmetries determined from experiment
  - These define Lagrangian
  - Theoretical predictions possible once Lagrangian is known
  - Experimental measurements validate or refute the theory
- BSM:
  - Theorists postulate new forces and interactions
  - Experimentalists look: find or rule out

Just because a theory is beautiful, doesn't mean it is correct!

- Example: SU(5) GUT
  - Developed by Georgi and Glashow in 1974
  - Simplest possible GUT
    - $\mathrm{SU}(5) \supset \mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)$
    - One fundamental coupling constant
    - Quarks and leptons in same multiplets
  - Beautiful theory that should have been right! But:
    - Predicts proton decay with lifetime $10^{30\pm2}$ years
    - Searches for proton decay (large water Cherenkov detectors) set lifetime limits outside predictions of minimal SU(5)
  - More complicted GUT theories still allowed

Particle physics experiment: The 3 frontiers

- Energy Frontier
  - Use high energy colliders to discover new particles and new interactions and directly probe the fundamental forces
- Intensity Frontier
  - Use intense particle beams or large mass detectors to uncover the properties of neutrinos and to observe rare processes that involve other elementary particles
- Cosmic Frontier
  - Use underground experiments and telescopes to study Dark Matter and Dark Energy. Use high energy particles from space to search for new phenomena



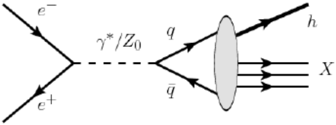
High Energy: Probing small distance structure

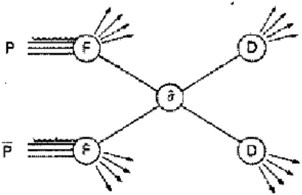
- Spatial resolution limited by wavelength of probe
  - Microscope: visible light $\lambda \sim 1\mu$m $\rightarrow$ cell structure
  - Higher energy particles: $\lambda = 2\pi\hbar/p$
    - $\hbar c \sim 200$ MeV fm
  - X rays: λ ~0.01-10 nm $\rightarrow$ atomic crystal structure

- Charged particles:
  - Rutherford experiment: $p \sim 10$ keV $\lambda \sim 10^{-10}$ m
  - Discovery of quarks: $p \sim 10$ GeV, $\lambda \sim 10^{-16}$ m
  - LHC: $p =$~1-10 TeV, $\lambda \sim 10^{-18}$ - 10^{-19} m
    - Can search for substructure (eg for quarks)

High Energy: Production of massive particles

- Energy mass equivalence: $E = mc^2$
- Mechanism for creating new massive particles: particle-antiparticle annihilation



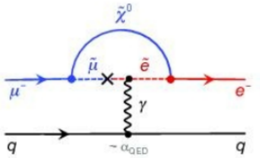


- e^+e- collider
  - Electrons have no internal structure
    - All energy used to make new particles
  - But electrons have small mass: radiate when accelerated

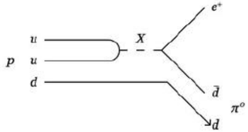
- Hadron collider
  - Protons made of q and g
    - Hard collision uses only fraction of energy
  - Protons heavy: less radiation when accelerated

High Intensity: Direct probes of large mass

- Virtual corrections have measureable effects
  - Ability to calculate size of these effects well established
    - $g-2$, precision measurements of Z-boson properties
- Size of correction depends on mass of exchanged particle
- If exchanged particle allows interactions forbidden by other processes, search for it through its virtual effects



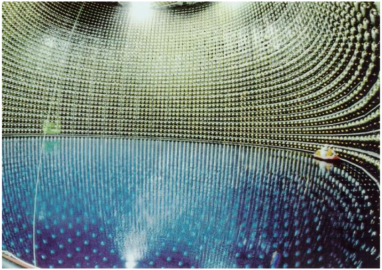
Lepton flavor violation: μ+N $\rightarrow$ e+N*

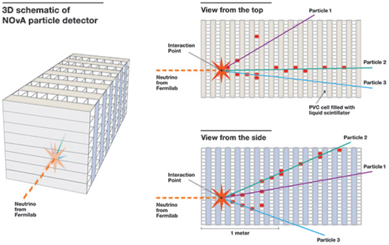


Proton decay in a GUT

Large Volume: Probing rare phenomena

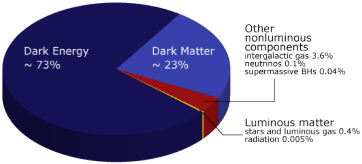
- If process rare, need many opportunities to see it
- Examples:
  - Neutrino interactions
  - Dark Matter (WIMPs)
- Detector is also the target
- Beams from accelerators or incident particles from outer space

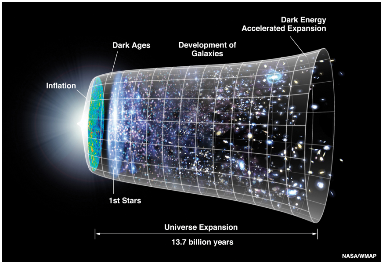




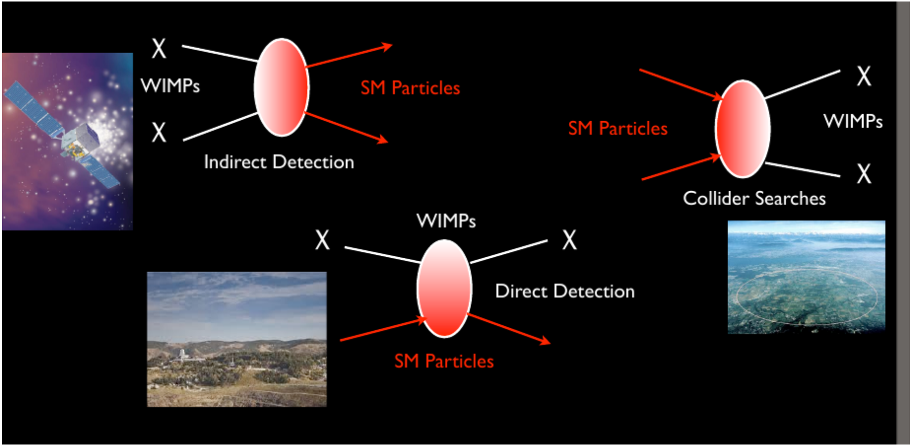
The Cosmic Frontier

- Most of the universe is not made of the particles we study in the lab
- Understanding Dark Matter and Dark Energy central to particle physics, although techniques used are quite different
- Significant synergy between particle physics and cosmology





Dark Matter: Three Complementary Approaches



Tim Tait: DarkMatter LHC 2013

Our program for the semester

- Experimental tools (2 weeks)
  - Detectors and accelerators
  - Statistics and probability
  - Fitting and other mathematical methods
- Particle physics basics (1.5 weeks)
  - Symmetries and conservation laws
  - Cross sections and Feynman diagrams
- Strong interactions (3 weeks)
  - Structure of the proton
  - The QCD Lagrangian
  - Hadronization
  - Quarkonium
- Weak Interactions (3.5 weeks)
  - Weak decays
  - C, P and CP
  - CKM Matrix
  - $K\overline{K}$ and $B\overline{B}$ Mixing
  - Neutral currents
- Hadron colliders (1.5 weeks)
  - Jet production
  - Electoweak bosons
  - The top quark
  - EWSB and the Higgs
- Current topics (2 weeks)
  - SUSY and GUTS
  - Dark Matter
  - Neutrinos